THE BEHAVIORAL ECONOMICS OF PRODUCTION

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In two experiments, thirsty rats licked an empty spout instrumentally for water delivered at a neighboring spout. Each such pair of spouts constituted a work station, and one, two, or three stations were available in the test enclosure. In 1-hr sessions, the rats worked alone or in the company of 1 or 2 other rats, and performed either five, 10, or 40 licks at the empty spout for each water delivery. The total number of empty-spout licks, summed across rats and stations, increased with the empty-lick requirement and, with some exceptions, the number of rats in the enclosure and the number of work stations available. A Cobb–Douglas production function, with instrumental responding as an output and the three independent variables as inputs, accounted for a significant percentage of the variance. Contrary to that function, output failed to increase with additional rats (or work stations) when the number of work stations (or rats) was relatively small.

Key words: behavioral economics, production function, Cobb–Douglas, thirst, water, lick, rats

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In laboratory experiments on economic behavior, it has become common practice to cast rats and pigeons in the role of consumer or laborer (Allison, 1983). This practice has proved successful in two domains of microeconomics: consumer demand, which deals with such matters as the relation between price and consumption (Allison, 1979; Allison, Miller, & Wozny, 1979; Allison & Wood, 1991; Bauman, 1991; Green & Rachlin, 1991; Hastjarjo, Silberberg, & Hursh, 1990; Hursh, 1980; Lea, 1978), and labor supply, which deals with such matters as wage rate and nonlabor income in relation to the amount of labor supplied by the individual (Allison & Boulter, 1982; Allison, Buxton, & Moore, 1987; Green, Kagel, & Battalio, 1987). There is a third domain, the economics of production, in which subjects are treated as an input in a production process. Here we examine a model for the economics of production, and describe two experimental tests of the model.

In economics, *production* refers to a process by which inputs in the form of various goods or services are transformed into an output in the form of some other good or service. A *production function* specifies the maximum output producible from the amounts of inputs used in the production process. A simple example of a production function is

$$Q = f(L, K), \qquad (1)$$

where L and K refer to labor and capital, respectively, and Q refers to the maximum output producible from the amounts of labor and capital used in the production process. For example, Q might refer to the number of automobiles produced, and L and K represent the amounts of labor and capital investment in the factory that produces the automobiles.

In manufacturing, empirical production functions are often obtained from cross-sectional data. A convenient form often assumed in such studies is the *Cobb–Douglas production function*. The best known form of this function, given three input variables denoted B, C, and D, is

$$Q = aB^bC^cD^d, \qquad (2)$$

where Q, a, B, C, and $D > 0$ and b, c, and $d \geq 0$ (Awh, 1976). From the logarithmic form of Equation 2,

$$\log Q = \log a + b \log B + c \log C + d \log D, \qquad (3)$$

one can estimate a, b, c, and d by means of linear multiple regression analysis. Note that when we write Equation 2 logarithmically, the exponents become coefficients of variables expressed in logarithmic units of relative magnitude. It follows that each exponent in Equation 2 is also an *output elasticity coefficient* that signifies the percentage change in output that results from a 1% change in the designated input.

In an example from the food-products industry (Awh, 1976), output was measured as
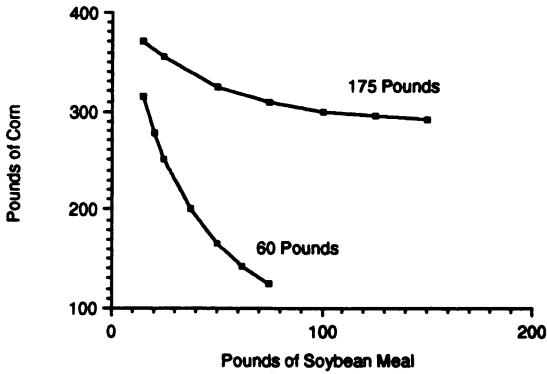
Fig. 1. Two isoquants: combinations of soybean meal and corn sufficient to produce a 100-lb gain in pigs with initial weights of 60 or 175 lb.

a function of three inputs whose estimated elasticity coefficients appear in parentheses: production worker (0.31), nonproduction employee (0.40), and capital (0.53). Thus, a 1% increase in production workers (or nonproduction employees, or capital) resulted in a 0.31% (or 0.40%, or 0.53%) increase in output. Note that the sum of the three coefficients is 1.24. Because the sum is greater than 1, this case illustrates *increasing returns to scale,* in that a 1% increase in all three inputs combined would result in a greater increase in output, 1.24%. If the sum of the three coefficients were less than (or equal to) 1, the case would illustrate decreasing (or constant) returns to scale (Awh, 1976). Long-run production functions typically show increasing or constant returns to scale (Smith, 1961).

Production processes are often clarified by means of isoquant maps. In the economics of production, an *isoquant* is a curve that shows different combinations of two inputs that produce the same output. Such curves are also called *isoproduct contours* (Smith, 1961). An example based on the work of Heady and Dillon (1961), on the production of pork, appears in Figure 1. The isoquant map shows the combinations of two different feeds, soybean meal and corn, that produced a 100-lb weight gain in pigs that initially weighed either 60 lb or 175 lb. Each isoquant slopes downward, indicating that each kind of feed functioned as a substitute for the other in the production of a 100-lb weight gain. The convexity of the isoquants shows that the feeds were imperfect substitutes; linear isoquants would indicate perfect substitutability. Note that the isoquant

is steeper for 60-lb pigs than for 175-lb pigs. Thus, as a substitute for corn, soybean meal (45% protein) functioned more effectively during the animal's growth stage (60-lb pigs) than it did later on (175-lb pigs), when weight gain became more a matter of fattening than of growth. Another well-known example, derived solely from technical information, involves the transmission of electric energy to a city through a power line from a hydroelectric dam. In that example, the substitutable inputs are the weight or size of the cable and the amount of electrical energy at the source (Smith, 1961).

In theory, isoquants have much the same properties as the indifference curves used in the theoretical analysis of consumer demand and labor supply. They are negatively sloped, convex to the origin, and show cardinal magnitudes—unlike indifference curves, which show only ordinal magnitudes. For example, if the curves in Figure 1 represented indifference curves, the upper curve would represent more utility than the lower, but the distance between the two curves would offer no guide to the magnitude of the difference in utility. With isoquants, the labels applied to the isoquants indicate cardinal magnitudes. Thus, the two isoquants in Figure 1 represent 100-lb gains on the part of 60-lb pigs and 175-lb pigs.

EXPERIMENT 1

In our first test of the model, rats licked an empty spout instrumentally for access to water. The output variable (E) was the total number of empty licks emitted in the 60-min session. We manipulated three input variables: the number of empty licks required for access to water (W), the number of rats in the test chamber (L), and the number of work stations available in the test chamber (K). We varied W by testing the rats under two different fixed-ratio (FR) requirements, 5 and 40 empty-spout licks; the contingent consequence was a fixed volume of water delivered at a nearby spout. We varied L by placing the rats in the test chamber in groups of 1, 2, or 3. Each work station consisted of an empty metal spout paired with a water-delivery spout. We varied K by providing the group being tested with one or two work stations. The three input variables were analogous to a piece-rate work requirement, labor, and capital. The function we assumed in advance was a Cobb–Douglas production

function,

$$E = aW^wL^lK^k. \tag{4}$$

Method

Subjects. The subjects were 12 experimentally naive Sprague-Dawley rats, 120-day-old females obtained from the Indiana University Psychology Department colony.

Apparatus. The rats were tested 1, 2, or 3 at a time in a large enclosure made of two identical operant conditioning chambers joined together. Each chamber was 26 cm wide, 24 cm deep, and 19 cm high. We joined them by removing their front doors and pushing the two chambers together, front to front, forming one large enclosure. The side walls, floor, and ceiling of each chamber were metal; the rear wall was opaque black plastic with a metal panel in the center.

Centered horizontally in the rear wall of each chamber was a row of three circular holes about 7 cm above the floor. The diameter of each hole was 16 mm, and adjacent holes were centered 32 mm apart. Behind each hole was a motor-driven shutter, mounted vertically and flush with the outside of the wall. The work station consisted of two metal spouts recessed 8 mm, one mounted behind the left shutter and the other behind the center shutter. The spout on the left had a smooth rounded tip with a 2-mm aperture; the one on the right was a Licksit spout with a spring-loaded valve stem. The right shutter was not used in this experiment, and stayed closed throughout. Just under the holes and 15 mm in front was a metal rod, 6 mm in diameter, that spanned the width of the chamber and served as a paw rest.

In test sessions, instrumental licks at the empty left spout operated a pump that dispensed water at the center spout. Licks at the left and center spouts were registered by an electronic drinkometer interfaced with the microcomputer (IBM® PC) that monitored and controlled experimental events. Completion of an instrumental requirement caused a calibrated pump to deliver 0.2 mL of water to the center spout. The water-delivery system is described more fully by Allison, Bailey, Mikesell, and Waltke (1991). Interior illumination came from two 2-W bulbs, one mounted on the ceiling of each chamber. A white-noise generator masked extraneous sounds.

Procedure. Before the first test session, we handled the rats, marked them, and pretrained

them individually in one of the small operant conditioning chambers. During the entire experiment, the rats had free access to food at all times. During pretraining, they had access to water in the home cage for 60 min each day. Before each pretraining session and each test session, we placed two pellets of Purina® Rat Chow 5012 in each chamber, for a total of about 10 g in each pretraining session and 20 g in each test session.

We pretrained the rats in a series of daily 30-min sessions just before their normal watering time. At the beginning of each session the left shutter opened, permitting access to the empty spout for the duration of the session. Completion of the first instrumental requirement operated the pump and opened the center shutter, permitting access to the center spout for the duration of the session. Because the center spout contained a priming load of 0.8 mL, this first pump operation left a total load of 1.0 mL in the center spout. At the end of the session, both shutters closed automatically. As the pretraining series progressed, we increased the instrumental requirement from FR 5 to FR 40 in a doubling series (5, 10, 20, and 40 empty-spout licks). We increased the requirement after any session in which the rat fulfilled the requirement at least once and consumed at least 90% of the water dispensed. The number of pretraining sessions ranged from 5 to 12.

Each test session lasted 60 min. The instrumental requirement was either 5 or 40 licks at the empty spout per pump operation. Any extra licks at the empty spout were counted against the next requirement. Thus, the rats could accumulate water up to the limit imposed by the capacity of the water spout (about 3.6 mL). Rats were studied individually, in pairs, and in groups of 3, and had access to either one or two work stations.

More specifically, each of the 12 rats received one test session in the 1-rat condition, two test sessions as a member of two different pairs in the 2-rat condition, and three test sessions as a member of three different triples in the 3-rat condition. Thus, each rat contributed $\frac{1}{12}$ of the data collected in the 1-, 2-, and 3-rat conditions. Each of the 12 pairs and each of the 12 triples was a unique combination of rats, and we used the same combinations in all phases of testing.

Half of the rats experienced the one-station condition first, in which they were tested with

Table 1

Total number of licks at the empty spout in Experiment 1.

				Number of stations					
				1			2		
				Number of rats					
Subject combinations			FR	1	2	3	1	2	3
1	2,3	4,5,6	5	277	437	620	279	1,004	459
			40	704	1,205	1,182	690	2,521	2,073
7	8,9	10,11,12	5	389	196	470	121	244	665
			40	1,539	1,162	793	870	1,472	1,643
6	1,2	3,4,5	5	136	260	185	344	639	1,087
			40	324	1,554	1,266	522	2,165	2,609
12	7,8	9,10,11	5	312	462	405	328	394	347
			40	607	160	573	1,048	1,463	1,680
5	1,6	2,3,4	5	138	309	407	307	553	1,396
			40	766	445	887	847	717	2,218
11	7,12	8,9,10	5	299	365	568	193	240	378
			40	398	743	801	972	2,124	1,626
4	5,6	1,2,3	5	235	194	521	163	424	1,187
			40	1,042	686	1,143	314	920	1,942
10	11,12	7,8,9	5	691	350	231	175	512	556
			40	142	290	641	613	2,060	2,328
3	4,5	1,2,6	5	240	474	356	267	508	996
			40	601	1,006	883	160	1,587	1,944
9	10,11	7,8,12	5	161	387	260	101	461	622
			40	64	281	721	705	1,537	2,081
2	3,4	1,5,6	5	415	490	339	553	918	649
			40	1,495	993	907	1,705	552	1,424
8	9,10	7,11,12	5	340	490	348	317	445	688
			40	912	619	504	908	1,143	1,610

FR 5 followed by FR 40. They were then switched to the two-station condition, in which they were tested with FR 40 followed by FR 5. The other half experienced the two-station condition first, in which they were tested with FR 5 followed by FR 40. They were then switched to the one-station condition, in which they were tested with FR 40 followed by FR 5. Thus, the design was completely balanced in terms of treatment order. The station was available in one chamber on half of the one-station tests and in the other chamber on the other half. We tested each rat 6 days each week. On the day off, the rats had free access to water in the home cage for 60 min.

On each test day, we tested one single, one pair, and one triple. About 5 min after each session, the rats that had just been tested received 10 min of free access to water in the home cage. Thus, on test days the daily water intake consisted of the water consumed during the test session plus any consumed in the free-access period right after the test.

Our principal measures were the total num-ber of licks at the empty spout(s) and total volumetric intake corrected for the amount, typically negligible, left in the water spout(s) or spilled as overflow. In the two-station condition, we recorded these measures separately for the two stations.

Results and Discussion

Table 1 presents the primary output data on which we based our analyses. It shows the total number of empty licks as a function of the number of stations available, the number of rats in the test enclosure, and the fixed-ratio requirement.

In accordance with Equation 3, a three-way analysis of variance applied to the total num-ber of empty licks showed that every main effect and interaction was statistically signifi-cant. The top panel of Figure 2 shows group means and standard errors with respect to the three-way interaction, $F(2, 33) = 3.96$, $p < .05$. Volumetric intake appears in the bottom panel. The two-way output interactions ap-pear in Figure 3; each main effect and each
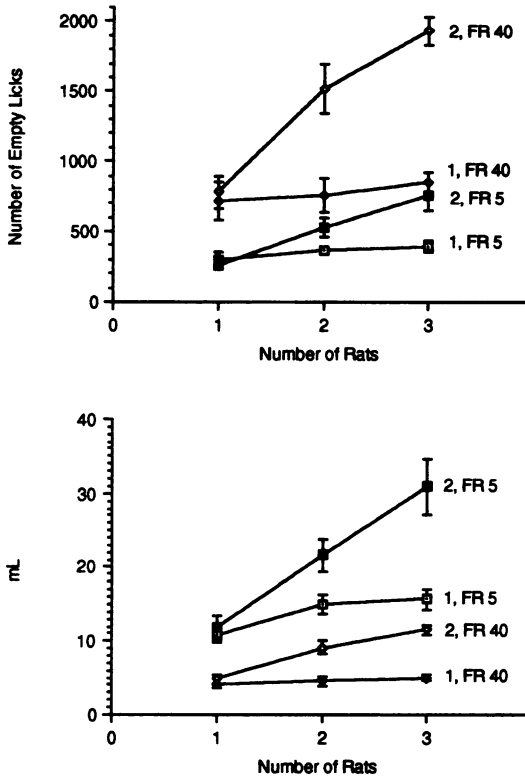
Fig. 2. Empty-spout licks (top panel) and water intake (bottom panel) as functions of the number of rats in the test enclosure (1, 2, or 3), the number of work stations available (one or two), and the empty-lick fixed-ratio requirement (5 or 40); group means and standard errors are shown.

two-way interaction was statistically significant at $p < .05$.

Multiple regression analysis applied to the 12 output means in the top panel of Figure 2 showed that Equation 4 accounted for a significant proportion of the variance; the adjusted multiple $R^2 = .88$, $F(3, 8) = 27.21$, $p < .001$. The intercept, a, was 118.16; t tests showed that each of the output elasticity coefficients was significantly greater than zero. The coefficient pertaining to W, the instrumental requirement, was 0.438, $p < .001$. The coefficient pertaining to L, the number of rats in the enclosure, was 0.551, $p < .01$. The coefficient pertaining to K, the number of work stations, was 0.591, $p < .01$. Thus, the following Cobb-Douglas production function accounted for much of the variance among the 12 group means:

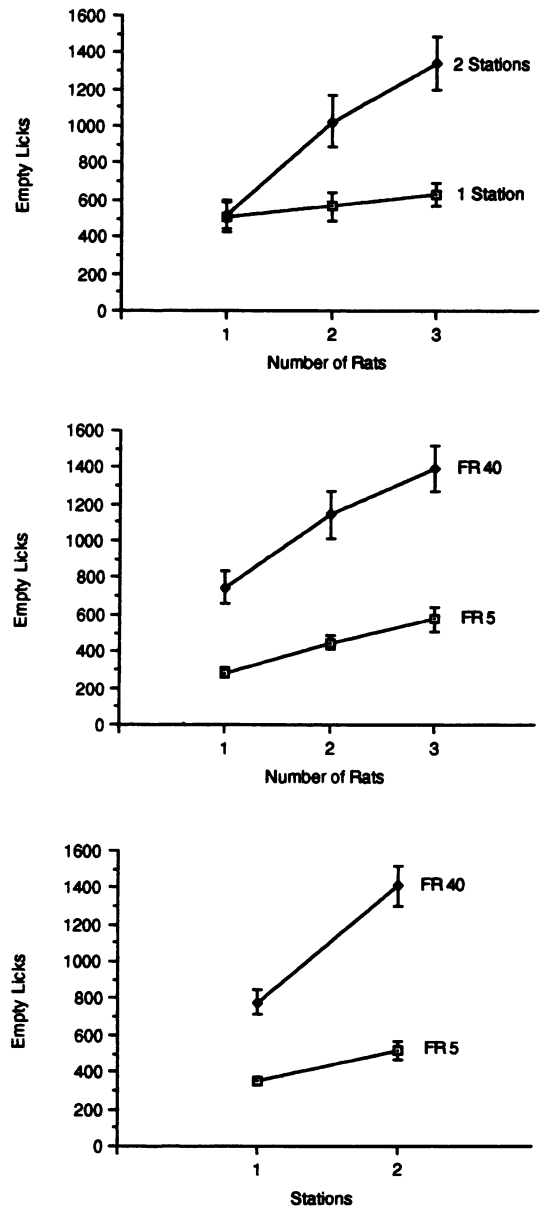$$E = 118.16W^{0.438}L^{0.551}K^{0.591}. \qquad (5)$$

Fig. 3. Empty-spout licks as a function of the number of rats in the test enclosure and the number of work stations available (top panel), the number of rats and the empty-lick fixed-ratio requirement (middle panel), and the number of stations and the fixed-ratio requirement (bottom panel); group means and standard errors are shown.

The top panel of Figure 4 compares the number of empty-spout licks predicted by Equation 5 with the number observed.

To test the significance of the differences among the three coefficients, it was necessary to obtain a distribution for each coefficient. We
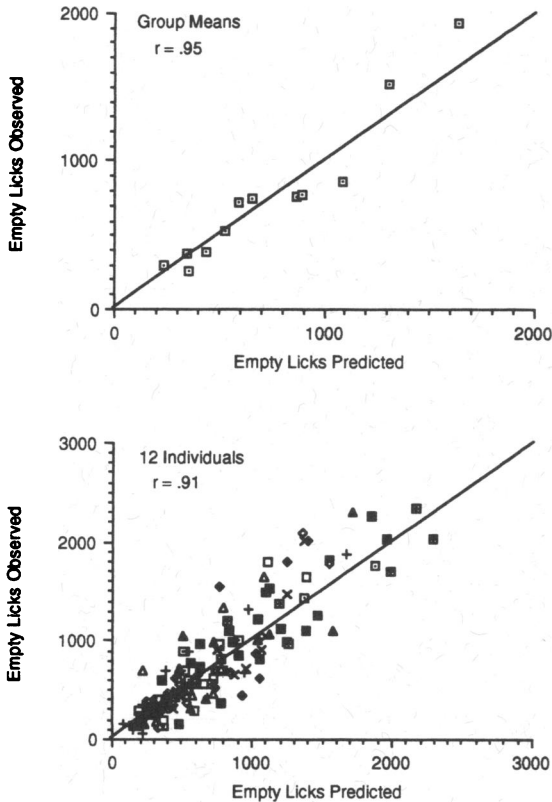
Fig. 4. Empty-spout licks observed as a function of empty-spout licks predicted by Cobb–Douglas production functions applied to group means (top panel) and individual rats (bottom panel).

obtained the necessary distributions by calculating 12 estimates for each coefficient, one estimate per rat. The key question in making these calculations was how to estimate a particular rat's performance during the 2-rat or the 3-rat condition. Without rat clones, we could not test the individual rat in the presence of 1 or 2 others genetically identical to it. However, we could estimate the performance of a particular rat under the 2-rat condition by calculating the mean of the two pairs of which it was a member. Similarly, we estimated the performance of a particular rat under the 3-rat condition by calculating the mean of the three triples of which it was a member. Note that each pair contributed to the estimates for 2 different individuals, and that each triple contributed to the estimates for 3 different individuals (see Table 1). Thus, the estimates of performance under the 2- and 3-rat conditions were quasi-independent, not independent.

The bottom panel in Figure 4 compares the number of empty licks predicted with the number observed for the 12 individuals. One-way analysis of variance revealed no statistically significant difference among the three coefficients, $F(2, 22) = 2.77$, $p > .05$. The means were 0.630 for the K coefficient, 0.415 for the W coefficient, and 0.693 for the L coefficient. The 95% confidence intervals showed that each coefficient was significantly greater than zero but was less than one, indicating a substantial but decreasing return to scale from each of the three inputs. The sum of the three coefficients ranged from 1.237 to 2.607 and had a mean of 1.738, indicating an increasing return to scale from the collective inputs. The intercept constant, a, had a mean value of 111.34, significantly greater than zero.

According to Equation 5, total output increased with the number of rats in the enclosure, even though the production per rat decreased. One indication of the drop in individual productivity is the pertinent output elasticity coefficient, 0.551. Its meaning is that a 1% increase in the number of rats was accompanied by a smaller relative increase in output, only 0.551%. Thus, we saw no "social facilitation" effect—no evidence that the presence of co-workers enhanced the productivity of the individual worker—but rather a social suppression effect.

Isoquants based on Equation 5 appear in Figure 5. Each isoquant shows the combinations of two inputs that would result in the same output, 1,000 licks at the empty spout. We calculated the top isoquant by assigning a value of 10 to the third input variable, the fixed-ratio requirement. We calculated the other two isoquants by assigning a value of unity to the third input variable. Each of the isoquants in Figure 5 slopes downward and is convex to the origin, like the theoretical isoquants discussed in the introduction. Therefore, the isoquants indicate that each of the three inputs functioned as an imperfect substitute for each of the other two inputs in the production of instrumental licks at the empty spout.

One of the variables manipulated in this experiment, the instrumental requirement, is already familiar to students of operant conditioning. Less familiar to them, but analogous to inputs well known to students of production, were the other two variables, the number of

rats in the test enclosure and the number of work stations provided. The instrumental responding that resulted from the interplay of these three variables formed a relatively complex data set that was described fairly well by a simple Cobb–Douglas function, one used widely in the study of production.

EXPERIMENT 2

Our first test of the model identified a new variable with major effects on instrumental performance, partly through its interaction with other variables. Indeed, the number of work stations available had an effect fully comparable to that of the fixed-ratio requirement and the number of rats in the test enclosure. The apparent power of this novel variable, the stations input, prompted us to explore it further in a second experiment.

Another reason for conducting the second experiment was the apparent weakness of the Cobb–Douglas function in predicting the effect of the labor input in the one-station condition. In Experiment 1, output increased markedly with the number of rats in the two-station condition but showed little or no change in the one-station condition (see the top panel in Figure 3). Our reanalysis of data reported by Grott and Neuringer (1974) in a similar one-station experiment also revealed no significant difference in output between 1 rat and 3 rats. In Experiment 2, we enlarged the enclosure on the chance that overcrowding induces competitive behavior inimical to production. In addition, we made videotapes of selected sessions to determine whether the test session was long enough to permit more rats to generate a greater output. For example, if 3 rats with access to one station spend a considerable proportion of the session away from the station, then the session is surely long enough to allow more output from 3 rats than from 2 or 1.

In Experiment 2 we tested the rats 1, 2, or 3 at a time in a triple chamber that offered either one, two, or three work stations. Because we wished to focus our efforts on these relatively unfamiliar input variables, time limitations forced us to drop the fixed-ratio requirement as a variable. Thus, the Cobb–Douglas function applicable to Experiment 2 was
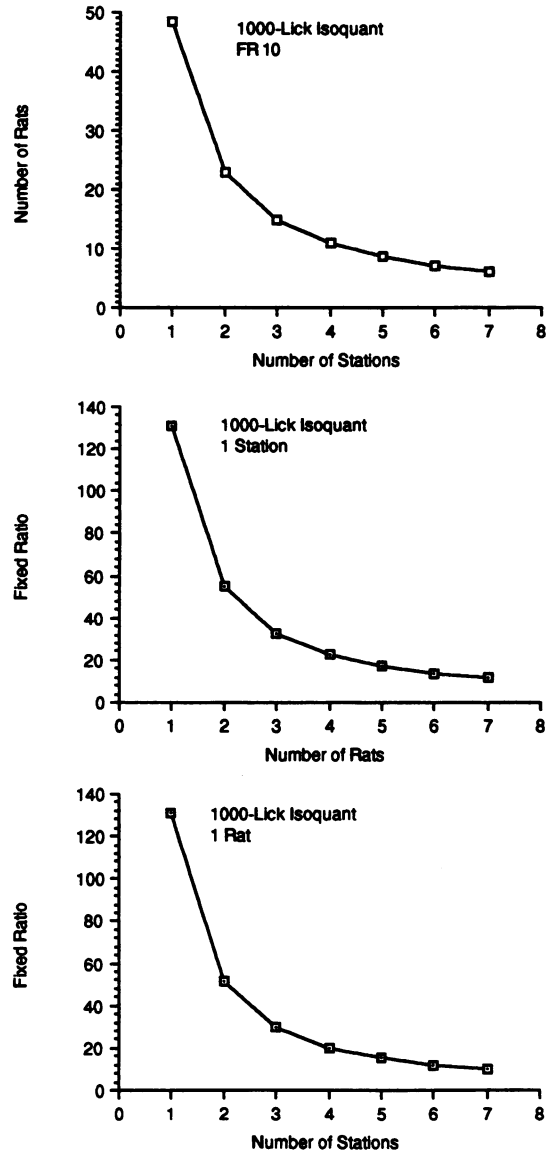

Fig. 5. Three isoquants: combinations of stations and rats (top panel), rats and fixed-ratio requirements (middle panel), and stations and fixed-ratio requirements (bottom panel) sufficient to produce 1,000 instrumental licks at the empty spout; data are based on a fitted Cobb–Douglas production function.

$$E = aL^l K^k \qquad (6)$$

where E, a, L, and $K > 0$ and l and $k \geq 0$. Equation 6 predicts two main effects and a divergent interaction. Specifically, output will increase with increases in L and K, and the effect of each of these two inputs will increase as the other input increases.

Table 2

Total number of licks at the empty spout in Experiment 2.

			Number of stations								
			1			2			3		
			Number of rats								
Subject combinations			1	2	3	1	2	3	1	2	3
1	2,3	4,5,6	518	201	332	605	333	526	489	279	493
6	1,2	3,4,5	421	753	103	288	947	151	407	764	125
5	1,6	2,3,4	63	688	208	112	474	412	154	1,095	479
4	5,6	1,2,3	253	1,068	490	44	831	521	285	835	676
3	4,5	1,2,6	32	512	684	63	490	1,232	39	725	1,375
2	3,4	1,5,6	393	151	450	363	462	1,079	315	332	1,417

Method

Subjects. The subjects were 6 experimentally naive Sprague-Dawley rats, 90-day-old females obtained from the Indiana University Psychology Department colony.

Apparatus. The rats were tested 1, 2, or 3 at a time in an enclosure obtained by joining three identical test chambers of the kind used in the first experiment. The junction provided a common antechamber with a triangular floor; the entrance to each chamber bounded one side of the equilateral triangle. The floor of the antechamber was sheet aluminum, and the triangular ceiling was a clear Plexiglas sheet drilled with several ventilation holes. A camcorder was mounted directly above the antechamber, 86 cm from lens to ceiling. Because the ceiling of each chamber was clear Plexiglas, the field of view through the lens of the camcorder covered the antechamber and nearly the whole of each chamber.

Procedure. We used the same procedure as that of the first experiment, with the following exceptions. Each rat was tested under FR 10 throughout the experiment, which was organized into six blocks of 3 consecutive test days. In the first block the 1-, 2-, and 3-rat combinations were tested with one work station the 1st day, two work stations the 2nd day, and three work stations the 3rd day. Each of the other blocks involved a new combination of rats and a new order of the work-station variable. Thus, the combinations experienced all possible orders of the work-station variable (Orders 123, 132, 213, 231, 312, and 321 were used in Blocks 1 through 6, respectively). After the first 18 test days, the rats received a second series of tests that replicated the first 18 test

days. Data analyses were based on the mean of the first and second series. We made videotapes of the last nine sessions that represented the complete experimental design (1, 2, or 3 rats tested with one, two, or three work stations).

During the entirety of each block, an individual rat was tested alone, with another rat, or with 2 other rats whose identity remained the same throughout the block. For the next block, the rats were rotated systematically to form a novel single, pair, and triple. Thus, at the end of the sixth block, each rat had contributed 1/6 of the data in the 1-rat condition, the 2-rat condition, and the 3-rat condition. Each rat worked 6 days each week and rested on the 7th, when it had water freely available in the home cage for 60 min.

Results

Informal analysis of videotapes showed that the rats spent a considerable amount of time away from the work stations, even when 3 rats had access to only one station. In the 2- and 3-rat conditions, much of this off-station time was allocated to a variety of social interactions, some of which appeared to be "aggressive," some not. Thus, it appeared that the test sessions were long enough to allow more output from 3 rats than from 2 or 1.

Table 2 presents the output data on which we based our analyses. It shows the total number of empty-spout licks as a function of the number of stations available and the number of rats in the test enclosure.

A two-way analysis of variance applied to the total number of empty-spout licks revealed the interaction predicted by Equation 6, but

only one of the two main effects. However, analysis of simple effects revealed a pattern quite similar to the one seen in Experiment 1. Group means and standard errors appear in Figure 6 with respect to total empty licks and volumetric intake. The predicted interaction with respect to total empty-spout licks is evident in Figure 6, $F(4, 30) = 2.75$, $p < .05$. Total output increased significantly as the number of work stations increased, $F(2, 30) = 5.04$, $p < .05$, but the number of rats had no statistically significant main effect, $F(2, 15) = 2.72$, $p > .05$. Analysis of simple effects showed that when three work stations were available, total output increased significantly as the number of rats increased, $F(2, 21) = 3.98$, $p < .05$. This "Rats" effect diminished as the number of work stations decreased: with two work stations, $F(2, 21) = 2.95$, $p > .05$; and with one work station, $F(2, 21) = 1.26$, $p > .30$. Similarly, output increased significantly with the number of stations available only in the 3-rat condition, $F(2, 21) = 9.64$, $p < .01$. Otherwise, the Stations variable had no significant effect: in the 2-rat condition, $F(2, 21) = 0.80$, $p > .40$; and in the 1-rat condition, $F(2, 21) = 0.10$, $p > .90$.

Multiple regression analysis applied to the nine output means in the top panel of Figure 6 showed that Equation 6 accounted for a significant proportion of the variance; the adjusted multiple $R^2 = .66$, $F(2, 6) = 8.74$, $p < .05$. The intercept, a, was 248.89. The coefficient pertaining to L, the number of rats in the enclosure, was 0.741. The coefficient pertaining to K, the number of work stations, was 0.263. Thus, the following Cobb–Douglas production function accounted for much of the variance among the nine group means:

$$E = 248.89L^{0.741}K^{0.263}. \qquad (7)$$

The top panel of Figure 7 compares the number of empty-spout licks predicted by Equation 7 with the number observed.

To determine whether the two coefficients differed significantly from each other and the values seen in Experiment 1, we obtained six individual estimates of each coefficient by the same method used in Experiment 1. The bottom panel in Figure 7 compares the number of empty-spout licks predicted with the number observed for each of the 6 rats. The means were 0.673 for the K coefficient and 1.368 for the W coefficient. The corresponding means
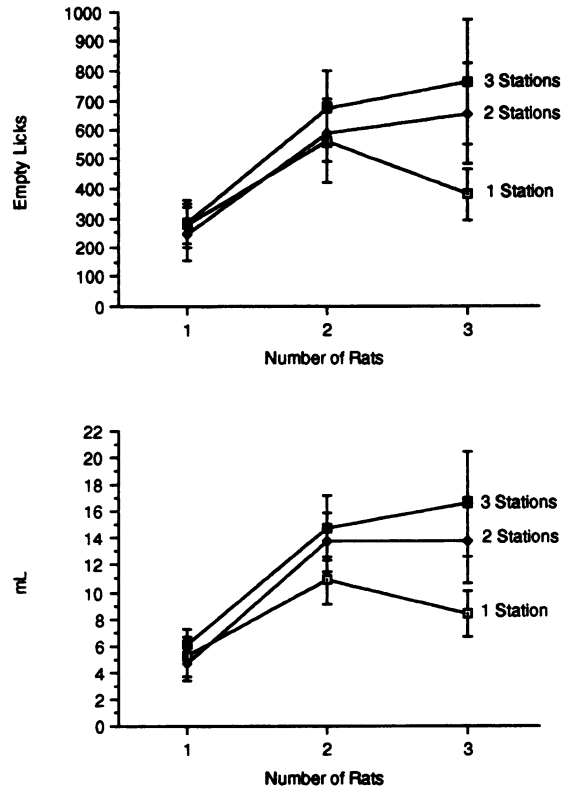

Fig. 6. Empty-spout licks (top panel) and water intake (bottom panel) as functions of the number of rats in the test enclosure (1, 2, or 3), and the number of work stations available (one, two, or three); group means and standard errors are shown.

in Experiment 1 were 0.630 and 0.693. Analysis of variance revealed a statistically significant Experiment by Coefficient interaction, $F(1, 16) = 4.40$, $p = .05$. Tests of simple effects showed that the K coefficient did not differ significantly between Experiments 1 and 2, but that the L coefficient was significantly higher in Experiment 2, $F(1, 27) = 5.80$, $p = .02$. And, although the two coefficients did not differ significantly in Experiment 1, in Experiment 2 the L coefficient was significantly greater than the K coefficient, $F(1, 16) = 7.98$, $p = .01$.

The reason for the increase in the L coefficient is open to speculation, but the salient difference was the larger enclosure used in Experiment 2. This difference suggests that the presence of other rats may distract a thirsty rat working for water, especially in cramped quarters. However, we should note that even though output was highly responsive to the
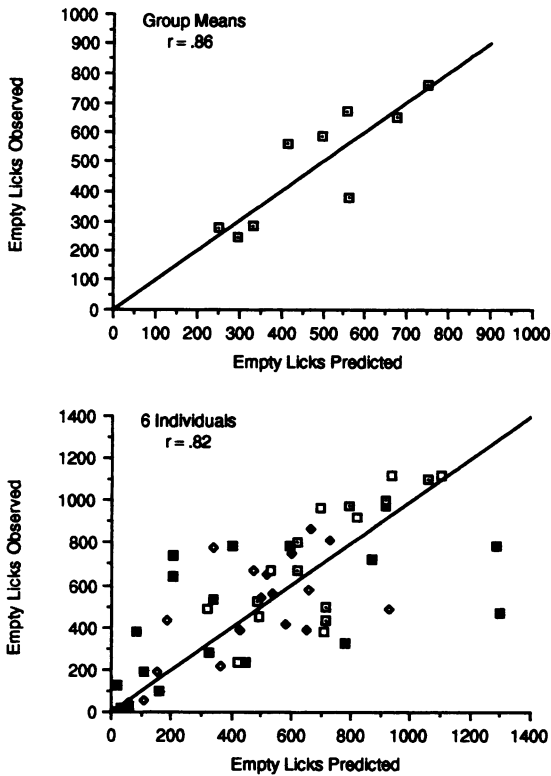
Fig. 7. Empty-spout licks observed as a function of empty-spout licks predicted by Cobb–Douglas production functions applied to group means (top panel) and individual rats (bottom panel).

labor input in Experiment 2, the labor variable still proved ineffective when work stations were relatively scarce. Similarly, the Stations variable proved ineffective when the number of rats was relatively small (see the top panels in Figures 3 and 6).

GENERAL DISCUSSION

We conclude that investigation of three domains of microeconomics—consumer demand, labor supply, and production—is now possible through the experimental analysis of the behavior of nonhumans. This conclusion is supported by the present results, in that the Cobb–Douglas production function accounted for a significant portion of variance in both experiments.

Because some of the remaining variance was systematic and not random, the results also proved useful in identifying a possible weakness of the standard function. Specifically, the

standard Cobb–Douglas function relating capital and labor consistently failed when the amount of capital or the amount of labor was relatively small. Therefore, the results suggest that the standard function applies only when a threshold amount of each input is available— a reasonable limitation typically not mentioned in standard accounts of production but clearly evident in our results.

In addition, we suggest that functions like Equations 2 and 3 might be valuable in the comparative study of nonhuman behavior or the study of individual differences. Output elasticity coefficients allow us to make unit-free comparisons of different variables in terms of their relative effects on output. In other words, output elasticity coefficients permit meaningful comparison of apples and oranges. Such coefficients could prove useful as descriptive statistics in comparing different animals' or different individuals' responses to a variety of common input variables. For example, independent variations in the behavioral cost, size, and chemical composition of a response-contingent food pellet would yield a separate elasticity coefficient for each of those three inputs. Analyses based on the three coefficients could both order the inputs in terms of their effects on instrumental performance and distinguish one species or one individual from another.

Although we focused in our own experiments on instrumental performance as the output variable, it is possible to analyze a variety of other measures as outputs of production functions. For example, a conventional measure of reproductive success might be analyzed as the output variable of a production function with inputs consisting of daily food intake, foraging time, and rate of energy gain (Lemon & Barth, 1992). We are confident that other investigators, representing a wide variety of orientations, can exploit and elaborate the basic concept of a production function in ways that we have not anticipated.

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